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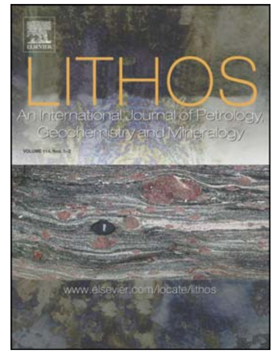

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Age of Alpine Corsica ophiolites revisited: insights from *in situ* zircon U-Pb age and O-Hf isotopes

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ABSTRACT

Knowledge of the age and timing of ophiolite sequences is essential for understanding the mechanisms of plate tectonics. The ophiolites in the Schistes Lustrés and the Upper nappes of Alpine Corsica represent remnants of the Liguria-Piemonte ocean basin that formed as a branch of the Central Atlantic basin during the opening of the Mesozoic Western Alpine Tethys. Despite numerous isotopic and paleontological studies, the age and timing of the ophiolites in the Schistes Lustrés nappe are still controversial. This study presents integrated *in situ* analyses of zircon U-Pb age and O-Hf isotopic data for ophiolitic gabbros and plagiogranites from three localities in the Schistes Lustrés nappe of Eastern Corsica. Our new results demonstrate that these rocks crystallized synchronously at ~159 Ma, approximately 10 m.y. younger than the ophiolites in the Balagne Upper nappe. Zircons from the gabbros and plagiogranites are characterized by highly positive εHf(t) (+15.0 to +15.9) and mantle-like $\delta^{18}O$ (5.2-5.4‰) values. Thus, these ophiolitic rocks were cogenetic, and crystallized from magmas produced by partial melting of a depleted, N-MORB type mantle. By contrast, in the Balagne Upper nappe, the ~169 Ma ophiolites contain numerous xenocrystic zircons inherited from a continental crust. Our current knowledge of isotopic geochronology and geochemistry supports a paleogeographic reconstruction, in which the earliest ophiolites in the Balagne nappe were emplaced close to a continental margin at ~169 Ma, whilst the N-MORB type ophiolites in the Schistes Lustrés nappe were likely formed approximately 10 m.y. later in the central part of the Liguria-Piemonte oceanic basin. The relative location of the Schistes Lustrés and Balagne Upper nappes with respect to continental margins is discussed.

Keywords: zircon U-Pb age; zircon O-Hf isotopes; ophiolite; Corsica; Alpine Tethys; Liguria-Piemonte oceanic basin

1 Introduction

The age and timing of ophiolitic sequences provide important constraints on the opening and palinspastic reconstructions of ocean basins, thus, knowledge of these sequences is essential for understanding the mechanisms of plate tectonics. The ophiolites exposed in Corsica, Northern Apennines, Liguria, and Western Alps represent remnants of the Liguria-Piemonte ocean basin that formed as a branch of Central Atlantic basin during the opening of the Mesozoic Western Alpine Tethys separating Adria from Europe (e.g., Lemoine et al., 1987). Precise chronology of oceanic opening is crucial to understand the Mesozoic evolution of the Alpine Tethys, and, in a more general way, to decipher how continents break apart and new oceans form.

Alpine Corsica is characterized by two main ophiolite-bearing tectonic units, namely i) the “Schistes Lustrés” nappe, composed of dismembered Jurassic ophiolitic elements enclosed by carbonate-rich mudstone and siltstone, globally called "schistes lustrés" (i.e. glimmering schists), and ii) the "Upper nappes" of Balagne, Nebbio, Macinaggio, Pineto and Rio Magno units (Fig. 1; Durand-Delga, 1974; Mattauer and Proust, 1975; Caron and Bonin, 1980; Mattauer et al., 1981; Durand-Delga and Rossi, 1991; Fournier et al., 1991; Egal, 1992; Padoa et al., 2001; Saccani et al., 2000; Saccani et al., 2008). The former experienced high-pressure/low-temperature (HP/LT) metamorphism, the latter only a weak prehnite-pumpellyite to low greenschist facies metamorphism, and in some cases no metamorphism (Lahondère, 1996;

Saccani et al., 2008; Vitale Brovarone et al., 2013). Both isotopic and paleontological age determinations have been conducted on Corsican ophiolites belonging to different structural units. Ohnenstetter et al. (1981) first reported an ID-TIMS U-Pb zircon age of 161± 3 Ma for two ophiolitic albitites from Punta Corbara and Vezzani from the Liguria-Piemonte HP/LT metamorphic “Inzecca series” of the Schistes Lustrés nappe. Rossi et al. (2002) reported a SHRIMP zircon U-Pb age of 169 ± 3 Ma for the plagiogranites from the weakly metamorphosed Balagne Upper nappe and recently a SHRIMP zircon U-Pb age of 152.5 ± 2.2 Ma for the trondhjemite of Rusio (15 km to the NE of Corte) on the same Liguria-Piemonte HP/LT unit from the metamorphic “Inzecca series” of the Schistes Lustrés nappe. Rampone et al. (2009) obtained a Sm-Nd isochron age of 155 ± 6 Ma for a gabbro noritic veinlet from the Mt. Maggiore peridotite sliver in the Schistes Lustrés nappe.

Biostratigraphically, numerous micropalaeontological data suggest that the radiolarian sediments overlying the basalt of the Balagne Upper nappe range between Upper Bathonian and Upper Callovian in age (Conti et al., 1985; Chiari et al., 2000; Peybernès et al., 2001a, b; Danelian et al., 2008), corresponding to a limited time span of 167-164 Ma according to the IGC Time Scale (Gradstein et al., 2004; Cohen et al., 2013). Unfortunately, away from this nappe that escaped the HP/LT metamorphic imprint, other cherts from the Schistes Lustrés nappe of Alpine Corsica never provided any consistent paleontological information. As radiometric ages are particularly rare, and an age discrepancy exceeding approximately 8 m.y. exists for some of the dated ophiolites from the Schistes Lustrés nappe, a need for new high precision dating appeared necessary.

Even for the best-preserved ophiolites, such as the Chenaillet massif in the Western Alps that escaped high-pressure metamorphism, zircons from the ophiolitic igneous rocks have been subjected to hydrothermal alteration resulting in elevated common Pb and altered O-isotopic values (e.g., Li et al., 2013a). Thus, a precise chronological knowledge is imperative for numerous Alpine Tethys ophiolites. Among the commonly-used radiogenic isotopic systems, zircon U-Pb and internal mineral Sm-Nd isochron have been widely used for dating ophiolites. For Mesozoic and younger ophiolitic rocks, Sm-Nd isotopic dating is rather imprecise due to the long half-life of ^{147}Sm (106 billion years), and limited fractionation in Sm/Nd ratios of major rock-forming minerals of ophiolitic rocks. Modern large radius magnetic sector SIMS (SHRIMP and Cameca IMS 1270/1280), in combination with cathodoluminescence (CL) images, have been shown to be successful in dating zircons from ophiolitic igneous rocks (e.g., Rossi et al., 2002; Rubatto and Scambelluri, 2003; Rubatto et al., 2008; Li et al., 2013a).

2. Aim of the study

In this study, we carried out integrated *in situ* zircon U-Pb age and O-Hf isotopic analyses for ophiolitic gabbros and plagiogranites (referred collectively as felsic plutonic rocks including diorite, quartz diorite, tonalite, trondjhemite and albitite) from three localities in the HP/LT Schistes Lustrés nappe located in the same group of structural units. The aim of the study was to: (1) provide new high-precision chronology for the Corsican Alpine ophiolites in order to better estimate the timing of spreading of the basin, (2) place new isotopic constraints on the genesis of these ophiolitic igneous rocks, particularly evidence for continental crust contamination through the presence of possible inherited zircons, and major variations in the Hf isotope ratio, and (3) discuss the paleoposition of the Corsican ophiolites within the Liguria-Piemonte ocean basin.

3. Geological background

Corsica consists of two major tectonic domains (e.g. Durand-Delga, 1974; Durand-Delga and Rossi, 1991, Rossi et al., 2009) namely, Alpine Corsica exposed to the northeast, and Variscan Corsica in the rest of the island (Fig. 1A). The Variscan basement is made up of a Carboniferous granitic batholith including rare septa of Paleozoic and Neoproterozoic sedimentary and metamorphic rocks (cf. Rossi et al., 2009; Faure et al., 2014; Li et al., 2014 for recent insights and references), and a Permian to Eocene sedimentary cover, partly reworked during the Alpine orogeny.

The Alpine belt of Corsica is a stack of west-directed nappes (Fig. 1B, C) (e.g. Durand-Delga, 1974; Mattauer and Proust, 1974; Mattauer et al., 1981;

Ohnenstetter et al., 1981; Faure and Malavieille, 1981; Malavieille et al., 1998; Fournier et al., 1991; Molli and Malavieille, 2011; Vitale Brovarone et al., 2013). It consists of three litho-tectonic units, from west to east, and from bottom to top: i) ductilely deformed Variscan basement, mostly exposed in the Tenda massif, and Vecchio area, in the north and south; ii) the "Schistes Lustrés” containing ophiolites; and iii) Upper undeformed units. Neogene sedimentary rocks unconformably overlie the nappe stack. A detail description of the structural and metamorphic evolution of Alpine Corsica is beyond the scope of this paper (see Molli and Malavieille, 2011, and Vitale Brovarone et al, 2013 for recent insights).

The Schistes Lustrés nappe is a composite tectonic structure formed by dismembered ophiolitic rocks, including serpentinized ultramafics, gabbros, pillow lavas, radiolarian cherts, siliceous shales, and ophiolitic sediments such as greywackes or gabbroic sandstones with mafic detritus (Lagabrielle and Lemoine, 1997; Vitale Brovarone et al., 2011). These rocks are sedimentary and tectonically associated with calcareous siltstone and phengitic metapelite, called "Schistes Lustrés". Furthermore, slices of continental crust rocks made up of ortho- and paragneiss, amphibolites, and Mesozoic metasandstones and marbles crop out in the Schistes Lustrés nappe. (Lahondère, 1981). These rocks derived from the easternmost part of the Corsican continental crust have been tectonically inserted into the Schistes Lustrés metasediments (e.g. Mattauer et al., 1981; Faure et al, 1981; Malavieille, 1983; Malavieille et al., 1998; Rossi et al. 2003; Meresse et al., 2012). The Pigno and Centuri units (Fig. 1) are among the largest examples of these continental slices. The Pigno area is composed of an assemblage of Variscan metagranite and metagabbro and diorite slivers sandwiched within alpine serpentinized mantle rocks and sediments (Lahondère 1981; Faure et Malavieille, 1981). According to Meresse et al. (2012), the pre-alpine basement slivers were considered as former extensional allochthons of continental crust abandoned during breakup of a newly exhumed seafloor of peridotite composition and the metasedimentary sequences that do not show affinities with the typical cover series of the Piemonte margin domains were reported to a more internal domain (oceanward). Owing to the high variability of the sedimentary successions as well as the presence of a basement composed of both continental and upper-mantle rocks, Meresse et al. (2012) proposed that this area was part of a Mesozoic Ocean–Continent Transition (OCT) of the Tethys basin. The ophiolitic slivers that occur as interleaved thrust slices within the complex stack of tectonic units of the Schistes Lustrés nappe, experienced HP/LT (blueschist and eclogites facies) metamorphism followed by a greenschist facies retrogression (e.g. Gruppo di Lavoro sulle Ofioliti Mediterranee, 1977; Ohnenstetter et al., 1981; Fournier et al., 1991; Caron, 1994; Lahondère, 1996; Miller et al., 2001; Miller, and Cartwright, 2006; Marroni and Pandolfi, 2007). The HT/LP metamorphism that is recorded in the Schistes Lustrés is one line of evidence that they were a part of a paleo-OCT.

This situation was recognised elsewhere in the hyper extended Laurentian margin during the early stage of the Iapetus ocean (Chew et al., 2003; van Staal et al., 2013).

Several units have been distinguished in the nappes of Corsica (Vitale Brovarone et al., 2013). Among the Upper units of Balagne, Nebbio and Macinaggio nappes that represent the uppermost part of the nappe pile of Alpine Corsica, the Balagne nappe contains Middle Jurassic (Bathonian-Callovian) ophiolitic rocks consisting of serpentinized mantle peridotites, gabbros, pillow lavas and deep sea sediments with radiolarian cherts and pelagic limestones. Furthermore, sandstones and breccias contain ophiolitic detritus, but also clasts of micaschist, rhyolite, and Middle Jurassic platform limestone. This detritus shows affinities with rocks of Western Corsica (Durand-Delga et al., 1997; Marroni and Pandolfi, 2003). In contrast, the Schistes Lustrés nappe, the Balagne Upper unit experienced neither the Alpine ductile shearing nor the HP/LT metamorphism, and appears to preserve only the effects of a low-temperature seafloor metamorphism (e.g. Warburton, 1986).

Sampling strategy. Six ophiolite samples were collected from the Schistes Lustrés nappe in this study for SIMS U-Pb age determination. Two ferrogabbro samples (11CO72 and 11CO73) were collected from Lento (N42°28'33'', E09°13'26''). They display similar mineral compositions, consisting of 60-65% plagioclase, 35-40% clinopyroxene and accessory minerals apatite, magnetite and zircon. The rocks are moderately altered as indicated by the occurrence of secondary sericite, actinolite and hematite. Sample 11CO75 is also a ferrogabbro that was collected to the northeast of Lento (N42°30'20'', E09°15'44''). It is composed of 55-60% plagioclase, 40% clinopyroxene, 1-5% hornblende and accessory minerals apatite, magnetite and zircon. The rock is altered, as shown by the alteration of plagioclase to sericite and zoisite, clinopyroxene to actinolite, and hornblende to chlorite and biotite. A gabbro sample (11CO78) was collected from Ortale de Biguglia, south of Bastia (N42°35'34'', E09°25'40''). It consists of ~50% plagioclase and ~50% clinopyroxene as well as accessory minerals of apatite, magnetite and zircon. Plagioclase is altered to sericite, epidote and zoisite whilst clinopyroxene is largely altered to tremolite. Close to the previous sample, a metamorphosed quartz diorite sample (2BDL165) was collected to the south of Bevinco (N42°36'08'', E09°25'45''). It consists of 70-75% plagioclase, 15-20% glaucophane and 5-10% quartz as well as accessory minerals apatite, magnetite and zircon. A trondhjemite (12BA10) was collected 500m to the SE of the village of Sampolo in the Inzecca canyon (N42°05'50", E09°16’33"). It experienced high-pressure metamorphism, consisting of 75-80% plagioclase, 15-20% stilpnomelane and 5% glaucophane as well as accessory minerals apatite, magnetite and zircon.

3 Analytical methods

3.1 Zircon and baddeleyite U-Pb dating

Zircon concentrates were separated from ~5-kg of gabbro and ~2-kg of quartz diorite and trondhjemite using standard density and magnetic separation techniques. Baddeleyite was separated from gabbro sample 11CO73. Zircon and baddeleyite grains, together with standard zircons 91500, Temora, Penglai and Qinghu as well as a baddeleyite standard Phalaborwa, were mounted in an epoxy mount that was then ground and polished to expose the crystals for analysis. Prior to SIMS analyses, the mount was vacuum-coated with high-purity gold.

Measurements of U, Th and Pb isotopes for zircon and baddeleyite were conducted using a Cameca IMS 1280 SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG-CAS) in Beijing, using analytical procedures of Li et al. (2009). For zircon and baddeleyite analyses, Pb/U fractionation and U and Th concentrations were calibrated against zircon standard 91500 (Wiedenbeck et al., 1995, 2004) and baddeleyite standard Phalaborwa (Heaman, 2009), respectively. Measured compositions were corrected for common Pb using non-radiogenic ^{204}Pb, apart from two plagiogranite (quartz diorite and trondhjemite) samples with variably high common Pb. An average of the present day crustal composition (Stacey and Kramers, 1975) is used for the common Pb. Data reduction was carried out using the Isoplot/Ex v. 2.49 program (Ludwig, 2001). In order to monitor the external uncertainties of SIMS U-Pb zircon measurements, an in-house standard zircon Qinghu was alternately analysed as an unknown together with other unknowns. Sixteen measurements on Qinghu zircon yield a Concordia age of 159.4 ± 1.2 Ma (2SE), which is in good agreement within errors with the recommended U-Pb age of 159.5 ± 0.2 Ma (Li et al. 2013b). Zircon U-Pb age data are presented in Appendix Table 1 and 2.

3.2 Zircon oxygen isotopes

Zircon oxygen isotopes were measured from the same domains that were previously analysed for U-Pb age determinations by using the same Cameca IMS 1280 SIMS at IGG-CAS, following the standard procedures of Li et al. (2010b). After U-Pb dating, the sample mount was reground and repolished to ensure that any oxygen implanted in the zircon surface from the O_2^- beam used for U-Pb determination was removed. A focused Cs^+ primary ion beam ("Gaussian beam") with an intensity of ~2 nA was accelerated at +10 kV. The spot size was about 10 μm in diameter. Oxygen isotopes were measured using multi-collection mode of two off-axis Faraday cups. Uncertainties on single analyses are normally better than 0.3‰ (2SE). The instrumental mass fractionation factor (IMF) was corrected using the zircon standard Penglai with a $\delta^{18}O$ value of 5.3‰ (Li et al., 2010c). A second zircon standard Temora was analysed as an unknown to ascertain the veracity of the IMF. Twelve measurements of Temora zircon standard during the course of this study yield a weighted mean of $\delta^{18}O$ = 8.24 ± 0.40‰ (2SD), which is consistent within errors with the reported value of 8.20‰ (Black et al., 2004).

3.3 Zircon Hf isotopes

Hafnium isotopes were measured on the same zircon grains that were previously analyzed for U-Pb and O isotopes, using a Neptune multi-collector ICP-MS equipped with the Geolas-193 laser-ablation system at IGG-CAS. Analytical procedures and isobaric interference corrections are similar to those described by Wu et al. (2006). Typical spot size for zircon Hf analyses was 63 μm in diameter, with ablation time of 26 seconds, repetition rate of 10 Hz, and laser beam energy density of 10 J/cm^2. Measured $^{176}Hf/^{177}Hf$ ratios were normalized to $^{179}Hf/^{177}Hf$ = 0.7325. Zircon standard Mud Tank was analysed alternately with the unknowns. During the course of this study, we obtained $^{176}Hf/^{177}Hf$ ratio of 0.282509 ± 0.000027 (2SD, n = 30) for Mud Tank zircon, in good agreement within errors with the recommended value of 0.282507± 0.000006 by solution MC-ICP-MS measurements (Woodhead and Hergt, 2005).

In situ zircon O and Hf isotopic results are listed in Appendix Table 3.

4. Analytical results

4.1 Zircon and baddeleyite U-Pb ages

(1) The Lento ferrogabbros

Zircons from three Lento ferrogabbro samples (11CO72, 11CO73 and

11CO75) have similar morphological and textural features. They are mostly transparent, 50-100 μm in length, and have aspect ratios of ~1:1 to 2:1. In CL images they are quite homogeneous, showing faint and broad zonation (Fig. 2).

Twelve analyses were conducted on 12 zircons from sample 11CO72 during a single analytical session (Appendix Table 1). These zircons are quite low in U (7-69 ppm) and Th (3-96 ppm); Th/U ratios vary between 0.29 and 1.40. Common Pb is variable, with seven analyses having f_{206} value (the proportion of common ^{206}Pb in total measured ^{206}Pb) lower than 0.80%, and the remaining five analyses relatively higher f_{206} values of 1.09-4.0%. All analyses form a single group of ^{206}Pb/^{238}U ratios within errors, corresponding to a weighted mean ^{206}Pb/^{238}U age of 158 ± 2 Ma (2SE, MSWD = 0.79) (Fig. 3).

Fifteen analyses were conducted on 15 zircons from sample 11CO73 during a single analytical session (Appendix Table 1). They have variable and low U (18-322 ppm) and Th (3-222 ppm) contents; Th/U ratios vary from 0.06-2.61. Common Pb is low, with f_{206} value < 1.4%. All analyses give indistinguishable ^{206}Pb/^{238}U ratios within analytical errors, with a weighted mean ^{206}Pb/^{238}U age of 158 ± 2 Ma (2SE, MSWD = 0.80) (Fig. 3).

Baddeleyite crystals coexisting with zircons were also separated from sample 11CO73. Baddeleyite crystals are mostly euhedral, transparent, 80-150 μm in length, and have aspect ratios of 2:1 to 3:1. Coarse zoning parallel to the crystal long axis is common in CL image (Fig. 2). Analyses were performed on 11 baddeleyite crystals. They have moderate U (62-219 ppm) but very low Th (all but one <1 ppm) contents; Th/U ratio are typically low, between 0.003 and 0.05 (Appendix Table 1). Common Pb is very low, f_{206} values are all <0.04%. The measured Pb/U ratios are indistinguishable within analytical errors (Fig. 4), yielding a weighted mean $^{206}Pb/^{238}U$ age of 159 ± 2 Ma (2SE, MSWD = 1.4). This age is identical within errors to that of the coexisting zircon Pb/U age of 158 ± 2 Ma.

Fourteen analyses were conducted on 14 zircons from sample 11CO75 during a single analytical session (Appendix Table 1). These zircons have highly variable U (19-914 ppm) and Th (15-720 ppm) contents; Th/U ratios vary between 0.11 and 1.38. Values of f_{206} are lower than 1.0%. All the measured Pb/U ratios are concordant within analytical errors (Fig. 3), a weighted mean $^{206}Pb/^{238}U$ age is calculated at 160 ± 2 Ma (2SE, MSWD = 1.3).

Overall, precise SIMS U-Pb zircon and baddeleyite measurements gave indistinguishable ages between 158 ± 2 and 160 ± 2 Ma for the ferrogabbro samples, which are interpreted as the best estimate of the crystallization age of the Lento ferrogabbros.

(2) The Ortale gabbro

Zircons from Ortale gabbro sample (11CO78) are transparent, 50-150 μm in length, and have aspect ratios of ~1:1 to 2:1. In CL images they are quite homogeneous, with faint and wide zones (Fig. 2). Sixteen analyses were conducted on 16 zircons during a single analytical session (Appendix Table 1). U and Th contents range from 24 to 331 ppm, and 12-795 ppm, respectively; Th/U ratios vary between 0.34 and 3.75. Common Pb is low; values of f_{206} are lower than 0.5%. Ratios of $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}Pb$ agree internally within the analytical precision (Fig. 3). A weighted mean $^{206}Pb/^{238}U$ age is calculated at 159 ± 1 Ma (2SE, MSWD = 0.71), which is interpreted as crystallization age of this gabbro.

(3) The Bevinco quartz diorite and Inzecca trondhjemite

Zircons from Bevinco quartz diorite sample (2BDL165) are transparent to semi-transparent, brownish in colour, 100-200 μm in length, and have aspect ratios of ~1:1 to 2:1. Zoning parallel to crystal faces is common under CL (Fig. 2); microfractures are often visible. Analyses were performed on 19 zircon grains during a single analytical session (Appendix Table 2). These zircons are characteristically low in U (14-53 ppm) and Th (6-38 ppm); Th/U ratios are between 0.30 and 0.80. Common Pb is highly variable; values of f_{206} range from 0.02% to 50.5%. For analyses with very high common Pb, common-Pb correction will result in very large uncertainty for radiogenic Pb isotopic ratios. Thus, we plot the common-Pb uncorrected isotopic ratios on the Tera-Wasserburg inverse U-Pb concordia diagram. All measured data define a discordia line with a lower-intercept age of 158 ± 3 Ma (2SE, MSWD = 2.6) (Fig.

5). This age is indistinguishable within errors from the weighted mean $^{206}Pb/^{238}U$ age of 159 ± 2 Ma (MSWD = 1.9) based on ^{207}Pb-correction (Appendix Table 2), which is interpreted as the timing of crystallization of this quartz diorite sample.

Zircons from Inzecca trondhjemite sample (12BA10) are transparent to semi-transparent, 100-200 μm in length, and have aspect ratios of ~1:1 to 2:1. Microfractures are visible in some zircons. In CL images they are relatively homogeneous and show faint zonation (Fig. 2). Analyses were made on 15 zircon grains during a single analytical session (Appendix Table 2). Similar to zircons from Ortale gabbro and Bevinco quartz diorite, the Inzecca trondhjemite zircons are also very low in U (11-34 ppm) and Th (3-11 ppm); Th/U ratios are fairly constant, between 0.26 and 0.44. Common Pb is variably high, values of f_{206} are between 1.07% and 36.9%. On the Tera-Wasserburg inverse U-Pb concordia diagram, all the common-Pb uncorrected data give a lower-intercept age of 159 ± 2 Ma (MSWD = 1.4), identical within errors with the weighted mean $^{206}Pb/^{238}U$ age of 159 ± 2 Ma (MSWD = 1.9) based on ^{207}Pb-correction (Appendix Table 2). Thus, we interpret the age of 159 ± 2 Ma as the best estimate of the timing of crystallization of the Inzecca trondhjemite sample 12BA10. This ageagrees with the previous TIMS U-Pb zircon age of 161± 3 Ma determined by Ohnenstetter et al. (1981).

4.2 *In situ* zircon O-Hf isotopes

(1) The Lento ferrogabbros

In situ O-Hf isotopic measurements were conducted on 41 zircons from three Lento ferrogabbro samples (11CO72, 11CO73 and 11CO75). Values of the measured $\delta^{18}O_{zir}$ are between 5.01‰ to 5.67‰ (Appendix Table 3), forming a Gaussian distribution. Thus, these Lento ferrogabbros exhibit homogeneous zircon oxygen isotopic compositions, with a mean $\delta^{18}O_{zir}$ value of 5.38 ± 0.35‰ (2SD) (Fig. 6).

These zircons yield $^{176}Yb/^{177}Hf$ ratio between 0.011 and 0.224 (Appendix Table 3), which are reasonably low for accurate isobaric interference correction (Wu et al., 2006). All the analyses give a small range of $^{176}Hf/^{177}Hf$ ratios between 0.283030 and 0.283184 (Appendix Table 3), corresponding to an average εHf(t) = +15.0 ± 3.0 (2SD).

(2) The Ortale gabbro

In situ O-Hf isotopic measurements were conducted on 18 zircons from the Ortale gabbro sample (11CO78). The measured $\delta^{18}O_{zir}$ values range from 5.08‰ to 5.64‰, forming a Gaussian distribution. Thus, these zircons have homogeneous oxygen isotopic compositions, with a mean $\delta^{18}O_{zir}$ value of 5.35 ± 0.33‰ (2SD) (Fig. 6). They have low $^{176}Yb/^{177}Hf$ ratio (<0.10); the $^{176}Hf/^{177}Hf$ ratios are between 0.283040 and 0.283194 (Appendix Table 3), corresponding to an average εHf(t) = +15.9 ± 3.0 (2SD).

(3) The Bevinco quartz diorite and Inzecca trondhjemite

Nineteen zircons from the Bevinco quartz diorite sample 2BDL165 were analyzed for O-Hf isotopes. They have a relatively wide range of the measured $\delta^{18}O_{zir}$ values varying from 4.20‰ to 5.40‰ (Appendix Table 3), forming a "skewed" distribution pattern (Fig. 6). It is noted that zircons with high common Pb (f_{206} = 50.4 - 9.8%) are low in $\delta^{18}O_{zir}$ values between 4.20‰ and 4.94‰. The origin of the low $\delta^{18}O$ zircons is discussed in detail later. Zircons with relatively low common Pb (f_{206} = 5.26 - 0.02%) have relatively high $\delta^{18}O_{zir}$ values between 5.01‰ and 5.40.‰, with the probability density function becoming more "Gaussian" in appearance (Fig. 6). These zircons give an average of 5.20 ± 0.22‰ (2SD) which is indistinguishable within analytical errors from the average value of 5.35 ± 0.33‰ for the Ortale gabbro. In contrast to the heterogeneous oxygen isotopes, all these zircons are fairly homogenous in Hf isotopes. They have slightly higher $^{176}Yb/^{177}Hf$ ratio (0.095 - 0.224) than the gabbro zircons. The measured $^{176}Hf/^{177}Hf$ ratios are between 0.283073 and 0.283189 (Appendix Table 3), corresponding to an average εHf(t) = +15.8 ± 2.7 (2SD).

Fifteen zircons from the Inzecca trondhjemite sample 12BA10 were analysed for O-Hf isotopes. The measured $\delta^{18}O_{zir}$ values range from 4.58‰ to 5.39‰ (Fig. 6). Two zircons with high-common Pb give relatively lower $\delta^{18}O_{zir}$ values of 4.58-4.81‰. The remaining zircons with low-common Pb have fairly homogeneous $\delta^{18}O_{zir}$ values of 5.06-5.39‰, with an average of 5.18 ± 0.24‰

(2SD). These zircons yield $^{176}Yb/^{177}Hf$ ratio of 0.087-0.127, which are in between those of gabbro zircons (mostly <0.10) and quartz diorite zircons (mostly >0.12). They have fairly homogenous $^{176}Hf/^{177}Hf$ ratios between 0.283073 and 0.283189 (Appendix Table 3), corresponding to an average εHf(t) = +15.5 ± 2.2 (2SD).

Overall, all analysed zircons from 4 gabbroic and 2 felsic samples have consistent εHf(t) values between +15.0 and +15.9 (Fig. 7).

5. Discussion

5.1 Formation age for ophiolites in the Schistes Lustrés nappe

Ophiolites from the Inzecca series of the Schistes Lustrés nappe were previously dated at 161± 3 Ma by ID-TIMS U-Pb zircon method for two ophiolitic albitites from Punta Corbara and Vezzani (Ohnenstetter et al.,1981), and at 153 ± 2 Ma on zircon of trondhjemite from Rusio (Rossi et al., 2012). A 155 ± 6 Ma age was obtained from an internal (plagioclase-whole rock-clinopyroxene) Sm-Nd isochron for a gabbronoritic veinlet from Mt. Maggiore peridotite (Rampone et al., 2009). It is noteworthy that common Pb is high for zircons from the Punta Corbara and Vezzani albitites, as shown by the low measured $^{206}Pb/^{204}Pb$ ratios, between 500 and 870 (Ohnenstetter et al.,1981), resulting in highly discordant $^{206}Pb/^{238}U$ (143-163 Ma) and $^{207}Pb/^{206}Pb$ (165-205 Ma) age results. In fact, high-common Pb is often observed in zircons from many Alpine Tethysian ophiolitic plagiogranites (e.g.

Ohnenstetter et al., 1981; Borsi et al., 1996; Costa and Caby, 2001; Rossi et al., 2002; Schaltegger et al., 2002; Rubatto and Scambelluri, 2003; Stucki et al., 2003; Rubatto et al., 2008; Li et al., 2013a; this study), because some of the plagiogranite zircons experienced hydrothermal alteration. The limited fractionation in Sm/Nd ratios of the analyzed minerals from ophiolitic gabbronorite (Rampone et al., 2009) make precise Sm-Nd isochron dating difficult.

Our new SIMS U-Pb zircon dating results give consistent crystallization ages of ~158-160 Ma for the ophiolitic gabbros from the Schistes Lustrés nappe. In addition, SIMS analysis gives a baddeleyite U-Pb age of 159 ± 2 Ma for the Lento ferrogabbro sample 11CO73, indistinguishable from the U-Pb age of 158 ± 2 Ma obtained from coexisting zircon.

Zircons from the Bevinco quartz diorite (sample 2BDL165) and Inzecca trondhjemite (sample 12BA10) with variably high proportion (up to 50%) of common Pb often show microfracture. These zircons are characterized by low $\delta^{18}O_{zir}$ values (4.2-4.9‰), lower than that (5.3 ± 0.3‰, 1SD) for zircons in high-temperature equilibrium with juvenile mantle-derived magmas (e.g. Valley et al., 1998, 2005; Valley, 2003). Thus, high common Pb in some zircons is attributed to post-magmatic hydrothermal alteration (see discussion below). By using the SIMS microanalytical technique, we have been able to target zircon domains at a scale of 20×30 μm to avoid visible alteration and microfracture. Despite some analyses showing variably high common Pb, the lower-intercept ages are well defined at 158 ± 3 Ma and 159 ± 2 Ma for sample 2BDL165 and 12BA10, respectively, obtained from low-common Pb (least-altered) zircon domains. Thus, these two ages can be interpreted as the timing of crystallization age of the diorite and trondhjemite, which are in good agreement with the crystallization ages of the ophiolitic gabbros.

To sum up, our new SIMS zircon and baddeleyite U-Pb data indicate that the ophiolitic fragments in the Schistes Lustrés nappe crystallized at ca. 159 Ma. Taking into account the uncertainties, the age of 158±3 Ma for the Bevinco quartz diorite marginally overlaps with the age of 153±2 Ma for Rusio trondhjemite (Rossi et al., 2012). Ophiolites from the Schistes Lustrés nappe are some 10 m.y. younger than the plagiogranites of the Balagne nappe dated at 169 ± 3 Ma by SHRIMP zircon U-Pb method (Rossi et al., 2002, Fig. 8). Thus, our new data support the paleogeographic reconstruction suggesting the more proximal position of the Balagne ophiolites with respect to a continental margin than the ophiolitic remnants enclosed in the Schistes Lustrés nappe (Beccaluva et al., 1977; Venturelli et al.,1979; Lahondère, 1996**;** Durand Delga et al., 1997; Principi et al.,2004; Saccani et al.,2008).

5.2 Isotopic constraints on genesis of ophiolitic igneous rocks

All analysed zircons from Lento and Ortale ophiolitic gabbros provide typical mantle-like $\delta^{18}O_{zir}$ value of 5.36 ± 0.34‰ (2SD, n = 59) and highly positive zircon εHf(t) value of +15.5 ± 3.0 (2 SD, n = 59), suggesting their crystallization from magmas that were produced by partial melting of a depleted, MORB-like mantle without any assimilation of continental crustal materials.

Zircons from the Bevinco quartz diorite and the Inzecca trondhjemite show variable $\delta^{18}O_{zir}$ values ranging from 4.2‰ to 5.4‰. Ten of 34 measured plagiogranite zircons yield $\delta^{18}O_{zir}$ values of <4.9‰, which are lower than those for zircons from the Lento and Ortale gabbros (~5.36‰) and zircons in high-temperature equilibrium with juvenile mantle-derived magmas (~5.3‰) (Valley et al., 1998, 2005; Valley, 2003). Three mechanisms may account for the genesis of the low-^{18}O zircons in the ophiolitic diorites. (1) These zircons were crystallized from low-^{18}O magmas that were produced by partial melting of oceanic gabbros that have been subjected to hydrothermal alteration at temperature above 200-250 °C, (2) they were reworked by high-pressure metamorphism during Alpine orogeny, and (3) the zircons were altered by subsolidus hydrothermal alteration.

The first mechanism is unlikely for the following reasons: hydrothermally-altered oceanic gabbros are characterized by $\delta^{18}O$ values lower than 5‰ (e.g., Muehlenbachs, 1986; Bindeman et al., 2005; Alt and Bach, 2006). Thus, if the plagiogranites were derived by partial melting of these altered, low-^{18}O oceanic gabbros, they should be uniquely low in $\delta^{18}O$ values. However, the majority of the plagiogranite zircons have $\delta^{18}O$ values higher than 5‰. Zircons with low common-Pb from the Bevinco quartz diorite and the Inzecca trondhjemite have $\delta^{18}O$ values of 5.20 ± 0.22‰ (2SD) and 5.18 ± 0.24‰ (2SD), respectively, which are indistinguishable within error from those of the gabbroic zircons. In addition, the Bevinco quartz diorite, the Inzecca trondhjemite, and other ophiolitic gabbros in the Schistes Lustrés nappe were crystallized synchronously at ~159 Ma, inconsistent with the formation of the felsic rocks by re-melting of the gabbroic rocks. High-pressure metamorphism could affect zircon O-isotopes to varying degrees (e.g., Fu et al., 2012). While all the gabbros and plagiogranites in the Schistes Lustrés nappe were overprinted by the Alpine high-pressure metamorphism, only those zircons with high common-Pb in plagiogranites are low in $\delta^{18}O$ values. In contrast, all the gabbro zircons preserve the O-isotope compositions of juvenile mantle-derived magmas. Therefore, an overprint by the Alpine high-pressure metamorphism seems unlikely as the major cause for the genesis of low-$\delta^{18}O$ zircons in plagiogranites, though this mechanism cannot be entirely excluded.

Low-$\delta^{18}O$ values are uniquely found in the high common Pb zircons in the plagiogranites, implying that low-^{18}O signatures might be intrinsically associated with the involvement of non-radiogenic Pb components. It is noted that microfracture is often visible in plagiogranite zircons. Microfractures usually provide a passageway for subsolidus hydrothermal fluids and/or metamictization, resulting in common-Pb addition and/or radiogenic Pb-loss (e.g. Corfu et al., 2003; Booth et al., 2005). Hydrothermal alteration is thought to be the major cause for many low-$\delta^{18}O$ zircons in altered ocean-crust (Grimes et al., 2011) and the Chenaillet albitites in the Western Alps (Li et al., 2013a). Thus, we argue that the low-$\delta^{18}O$ zircons in the Bevinco quartz diorite and the Inzecca trondhjemite were attributed to subsolidus hydrothermal alteration. Despite modifying the O-isotopes, hydrothermal alteration has little impact on Hf-isotopes recorded by these low-$\delta^{18}O$ zircons. Moreover, the majority of low common-Pb zircons still preserve their primary oxygen isotopic compositions. Thus, the plagiogranites show similar zircon U-Pb age and O-Hf isotopic signatures to the gabbros, suggesting that the all these rocks were likely cogenetic, with the plagiogranites being formed by extreme fractional crystallization from basaltic magma.

5.3 Implications for opening and palinspastic reconstruction of the Liguria-Piemonte ocean basin

High-precision geochronology of ophiolites can be used to constrain the timing of opening and palinspastic reconstructions of ancient oceanic domains. Based on the recent compilation of reliable U-Pb zircon ages (Li et al., 2013a and references therein), and the new U-Pb age data in this study, the majority of the Alpine Tethys ophiolitic rocks were formed at ~158-169 Ma, indicating a fairly short life-span of ~11 m.y., rather than a ~30 m.y. life span as previously thought (e.g. Costa and Caby, 2001). Among them, the Corsican Alpine ophiolites dated at ~158-160 Ma in the Schistes Lustrés nappe are the youngest, whilst those dated at ~169 Ma (Rossi et al., 2002) in the Balagne Nappe are the oldest (Fig. 8). Thus, they might represent two distinct portions of the Liguria-Piemonte oceanic basin (Beccaluva et al., 1977; Venturelli et al.,1979; Principi et al.,2004; Saccani et al.,2008).

Zircon Hf isotopic data, despite being less abundant than radiometric ages, have also been reported for other ophiolites from the Chenaillet nappe in the Western Alps, and the Platta and Err Nappes in the Eastern Central Alps. The Chenaillet troctolites and albitites dated at ~165 Ma have εHf(t) = +13.0 to +13.5 (Li et al., 2013a); the Platta and Err gabbros and albitites dated at ~161 Ma have εHf(t) = +14.4 to +14.9 (Schaltegger et al., 2002). Our new analyses indicate that the gabbros and plagiogranites dated at ~159 Ma in the Schistes Lustrés nappe of Corsica have εHf(t) = +15.0 to +15.9. These highly positive εHf(t) values point to their derivation from highly depleted, MORB-like mantle sources. It is interesting to note that these εHf(t) values, despite indistinguishable within analytical errors, increase slightly with decreasing age. If this correlation is true, the most depleted mantle source would be invoked for the younger ophiolitic rocks as previously proposed by Saccani et al. (2008).

In contrast to derivation from a highly depleted MORB-like depleted mantle source for the ~159 Ma ophiolites in the Schistes Lustrés nappe, the ~169 Ma ophiolites in the Balagne nappe contain numerous ancient xenocrystic zircons derived from a continental crust (Rossi et al., 2002). It is suggested that the E-MORB type ophiolites in the Balagne nappe were emplaced within the OCT in the very marginal part of the Liguria-Piemonte oceanic basin, and the N-MORB type ophiolites in the Schistes Lustrés nappe were formed approximately 10 m.y. later in the most central part of the ocean (Rossi et al., 2002).

The division between (depleted) N-MORB and (enriched) E-MORB (or T-MORB) has been discussed (Arevalo and McDonough, 2009) and was re-examined for ophiolites from the Western Tethyan realm in External Liguride, Alpine, and Corsica. Many of the previously interpreted N- or E-MORB ophiolite were re-interpreted as N-MORB-type with a marked garnet signature resulting from partial melting of a depleted N-MORB type source bearing garnet-pyroxenite relics left by the delamination of the sub-continental mantle at the OCT zone (Montanini et al., 2008; Piccardo, 2008; Saccani et al., 2008). Basalts with garnet signature or G-MORB (Garnet-influenced MORB; Saccani, 2014) corresponding to C-MORB (Dilek and Furnes, 2011) characterize the OCT.

The integration of high-precision U-Pb zircon geochronology, trace element composition, zircon Hf isotopic compositions reflective of the nature of mantle sources, and other aspects of geological observations by previous authors enable us to discuss the paleoposition of the Corsican ophiolites in the Liguria-Piemonte ocean basin (Fig. 9).

Presently, available radiometric, bulk geochemical and isotopic data, as well as biostratigraphy and sedimentology (summarized in section 3), argue for a more proximal position (i.e. close to continental margin) of the Balagne ophiolite than the Schistes Lustrés ophiolites. It is also well documented that both the Schistes Lustrés nappe and the Upper units (Balagne, Nebbio, Maccinagio) were displaced from east to west. Moreover, from a simple geometric point of view, mapping shows that the Upper units tectonically overly the Schistes Lustrés nappe (Fig. 1C). Thus the questions are: 1) to which margin does the Balagne nappe belong, and 2) how to reconstruct the paleogeography of the Liguria-Piemonte ocean? These questions were debated for a long time since Kober (1928), Mattauer and Proust (1975) Durand Delga et al. (1997), Lahondère (1996) and still more recently (e.g. Rosenbaum and Lister, 2005; Marroni and Pandolfi, 2007; Handy et al., 2010; Molli and Malavieille, 2011).

According to Meresse et al. (2012), the continental units of Centuri and Pigno (Fig 1), enclosed in the Schistes Lustrés nappe, belong to an OCT. Therefore, two OCT's were documented in Corsica. On one hand, the "Pigno OCT" is intensely sheared and metamorphosed and crops out in the Schistes Lustrés nappe in contrast to the less deformed and weakly metamorphosed Balagne Upper unit. Assuming that there was only one Liguria-Piemonte oceanic basin, the Pigno OCT would likely represents the easternmost highly extended continental margin of the Corsica continent. The weakly deformed and metamorphosed Balagne OCT on the other hand might either represent the eastern margin of the Liguria-Piemonte Ocean, belonging to the future upper plate during the Alpine orogeny (Fig. 9A), or a marginal basin in its western margin (Fig. 9B). Constrained by its Apenninic affinity, the paleolocation of the E-MORB Rio Magno Unit (Padoa et al., 2001) was reported (Padoa et Durand Delga, 2001) to the internal “igurides” Ligurides that escaped from deep involvement during the “Apenninic” subduction beneath the European continental margin.

The determination of which continent it might be, either Adria or AlKaPeCa, is beyond the scope of this paper (see Molli and Malavieille, 2011 for discussion). It is worth noting that geological arguments related to the provenance of detrital elements as well as geochronological and geochemical criteria to solve this question are quite difficult to use since the Liguria-Piemonte ocean opened in late Middle Jurassic within a continental crust formed in the Variscan orogeny. Thus, similar Paleozoic magmatic and metamorphic rocks, and Triassic to Early Jurassic sedimentary sequences should be encountered on both continental margins if the continental breakup was not superimposed to (or inherited from) a previous paleogeographical boundary.

The Balagne nappe may alternatively belong to the European margin (Fig. 9B, after Rossi et al. 2002) because the oceanic basin was fed from the Middle-Upper Jurassic, by detrital sediments and zircons which have been derived from specific rock types restricted to the Western Corsica basement

(European plate) such as Mg-K or hypersolvus granites (Durand-Delga et al., 1997). This is similar to the opening of the South China Sea, a hyper extended margin where a complex OCT was developed (Savva et al., 2014). In this location, granitic blocks are enclosed by exhumed mantle areas as a result of boudinage. This is a possible proxy of the model suggested for the European Liguria-Piemonte OCT at the margin of the Corsica-Sardinia batholith (Rossi and Cocherie, 1991). This alternative palinspastic reconstruction model, however, needs to explain the absence of ductile shearing and syntectonic metamorphism in the Balagne nappe. If this unit is interpreted as a "proximal" and thus close to the Corsican continental margin, it would have experienced an intense synmetamorphic ductile deformation both during continental subduction and exhumation, however such features are presently lacking.

6 Conclusions

Regardless of the discussion related to continental margin position of the Balagne ophiolite within the Liguria-Piemonte ocean, our new SIMS U-Pb zircon and baddeleyite dating demonstrates that in Alpine Corsica, the ophiolitic magmatic rocks (gabbro, quartz diorite and trondhjemite) found in the Schistes Lustrés nappe crystallized synchronously at ~159 Ma, that is approximately 10 m.y. younger than the ophiolites of the Balagne Nappe. Zircons from the gabbros and plagiogranites are characterized by highly positive εHf(t) (+15.0 to +15.9) and mantle-like $\delta^{18}O$ (5.2-5.4‰) values, indicating they were cogenetic, and crystallized from magmas that were produced by partial melting of a depleted, MORB-like mantle. The ophiolites in the Schistes Lustrés nappe, characterized by the most depleted Hf isotopic compositions, represent the youngest remnants of the western part of the Liguria-Piemonte ocean basin. By contrast, the ~169 Ma ophiolites in the Balagne nappe, having numerous xenocrystic zircons inherited from a continental crust, represent the oldest, and most marginal remnants of the Liguria-Piemonte oceanic basin emplaced upon the Corsica continental margin.

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Figure captions

Fig. 1 A: Location of Corsica in the Alpine framework, B: Simplified structural map of Alpine Corsica showing the distribution of ophiolite-bearing units of the Schistes Lustrés nappe and Upper units (Balagne). Radiometric ages available in the literature: (1) Ohnenstetter et al. (1981); (2) Rossi et al. (2002); (3) Rossi et al. (2012); (4) Rampone et al. (2009). C: Cross section through the Corsican Alpine stack of nappes (located in B). Figures are modified after Malavieille et al. (1998), Miller et al. (2001), and Vitale Brovarone et al. (2013).

Fig. 2 Cathodoluminescence (CL) images for representative zircons from the Corsican ophiolitic rocks. The yellow ellipses in the CL images represent the spots of SIMS U-Pb and O isotope analyses. SIMS spots are 30 μm in length for scale.

Fig. 3 Conventional zircon U-Pb concordia plots for the Lento ferrogabbros (11CO72, 11CO73 and 11CO75) and the Ortale gabbro (11CO78).

Fig. 4 Conventional baddeleyite U-Pb concordia plot for the Lento ferrogabbro (11CO73).

Fig. 5 Inverse zircon U-Pb concordia plots for the Bevinco quartz diorite

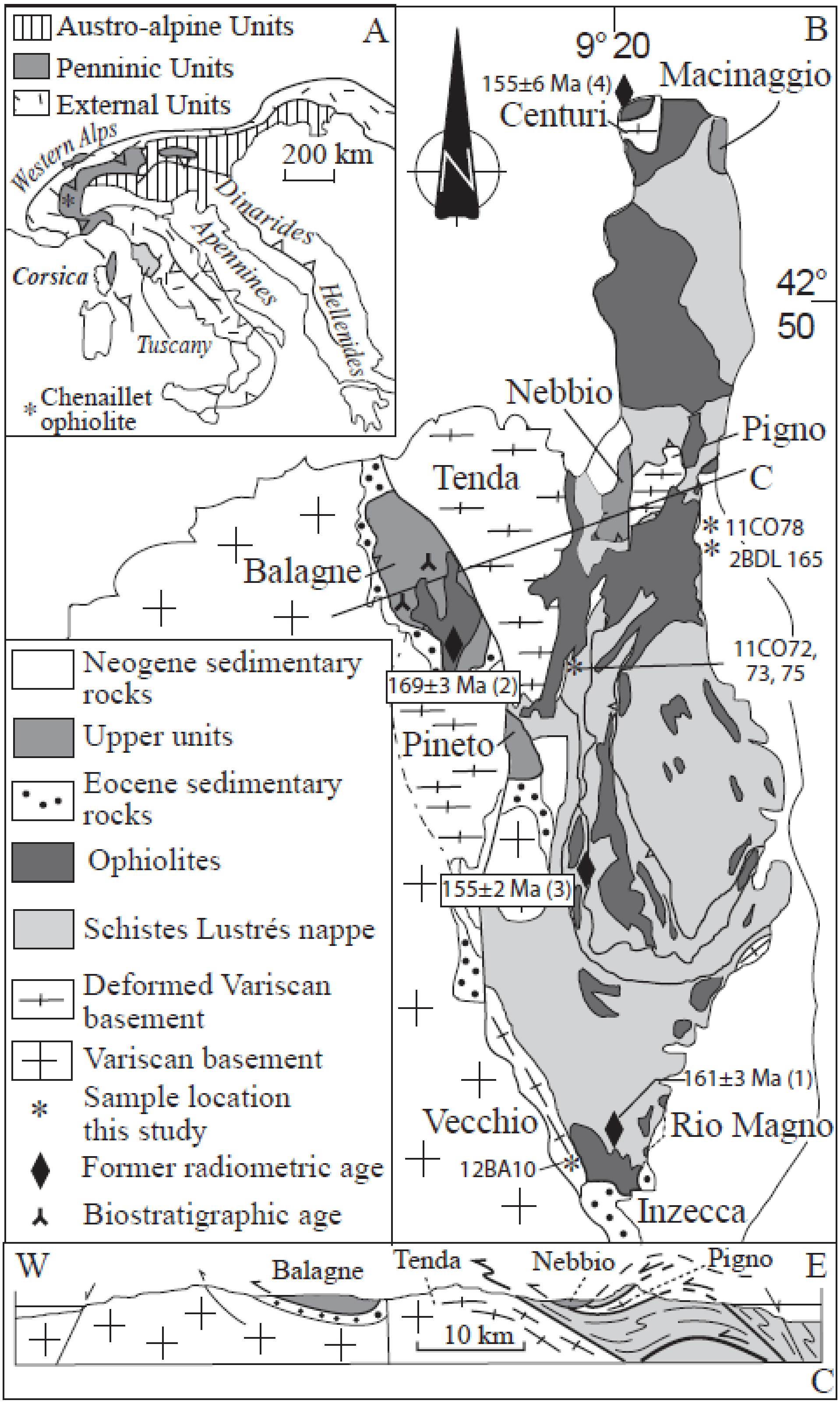
(2BDL165) and the Inzecca trondhjemite (12BA10).

Fig. 6 Probabilistic histograms of zircon $\delta^{18}O$ values for the ophiolites in the Schistes Lustrés. The bold line on each plot is a probability density function for all determined zircons; while the dashed lines are probability density functions for zircons from sample 2BDL165 and 12BA10 that are not affected by high common Pb.

Fig. 7 Probabilistic histograms of zircon εHf(t) values for the ophiolites in the Schistes Lustrés.

Fig. 8 Synoptic plot of available radiometric and biostratigraphic constraints for the Liguria-Piemonte ocean. Zr: zircon U-Pb SHRIMP, Sm/Nd: Sm/Nd whole rock ages. The Corsican ophiolites ages range mostly from 169 Ma to 158 Ma (possibly to 152 Ma?). References: (1) Ohnenstetter et al. (1981), (2) Rossi et al. (2002), (3) Rossi et al. (2012), (4) Rampone et al. (2009), (5) Tribuzio et al. (2004), (6) Kaczmarek et al. (2008), (7) Stucki et al. (2003), (8) Schaltegger et al. (2002), (9) Danelian et al. (2008), (10) Bill et al. (1997), (11) Li et al. (2013a).

Fig. 9 Two alternative palinspastic reconstructions of the Liguria-Piemonte ocean basin showing the possible paleogeographic relationships between the Corsican continental basement (Tenda, Pigno) and the ophiolite complexes exposed in the Balagne and Schistes Lustrés nappes. A: The Balagne ophiolites belong to the Eastern continental margin of the ocean, like the Chenaillet ophiolitic massif. These units that were emplaced above the western continent, escaped the high-pressure metamorphism and ductile deformation. B: The Balagne ophiolites belong to an oceanic crust close to the Western continental margin of the Liguria-Piemonte ocean (modified from Rossi et al., 2002). See text for discussion.



A
Austro-alpine Units
Penninic Units
External Units
Western Alps
200 km
Dinarides
Apennines
Hellenides
Corsica
Tuscany
Chenaillet ophiolite
B
9° 20
155±6 Ma (4)
Centuri
Macinaggio
42° 50
Nebbio
Pigno
C
Tenda
11CO78
2BDL 165
Balagne
11CO72, 73, 75
169±3 Ma (2)
Pineto
155±2 Ma (3)
161±3 Ma (1)
Rio Magno
Vecchio
12BA10
Inzecca
Neogene sedimentary rocks
Upper units
Eocene sedimentary rocks
Ophiolites
Schistes Lustrés nappe
Deformed Variscan basement
Variscan basement
Sample location this study
Former radiometric age
Biostratigraphic age
W
Balagne
Tenda
Nebbio
Pigno
E
10 km
C

Figure 1

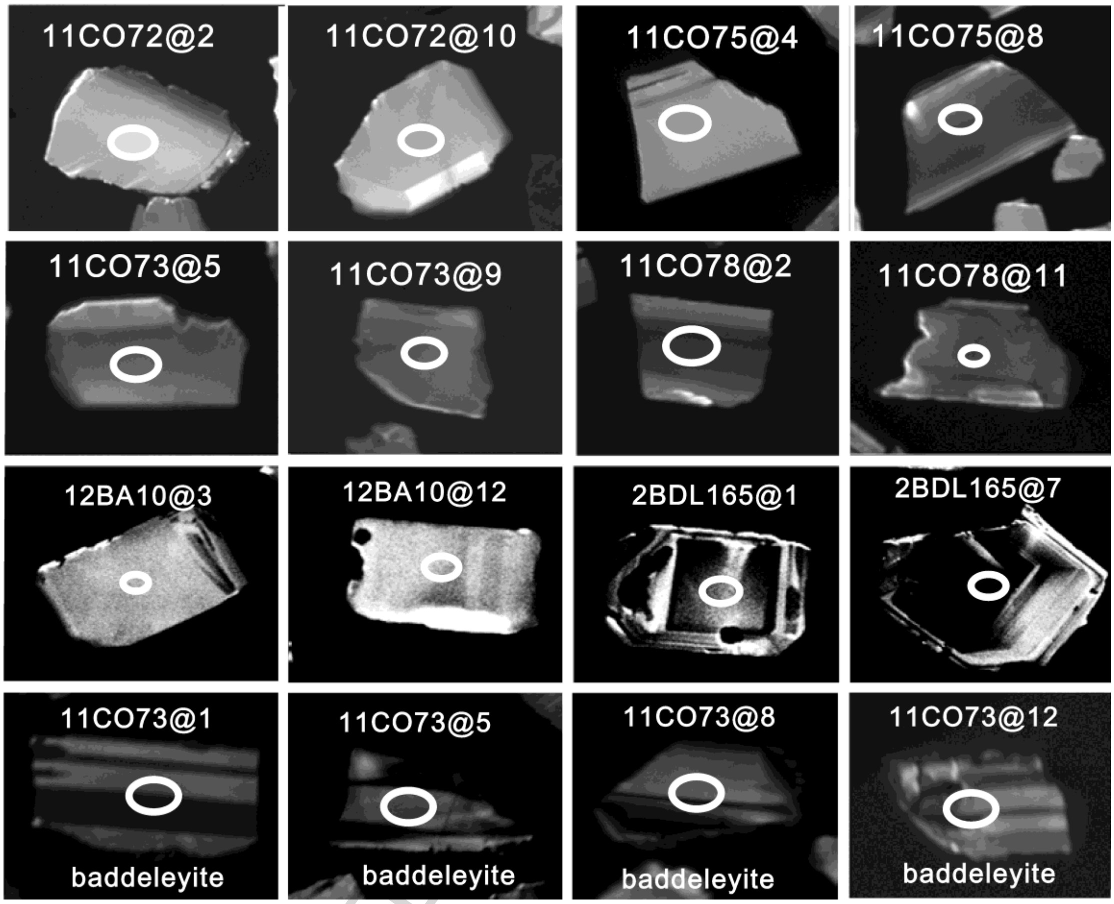
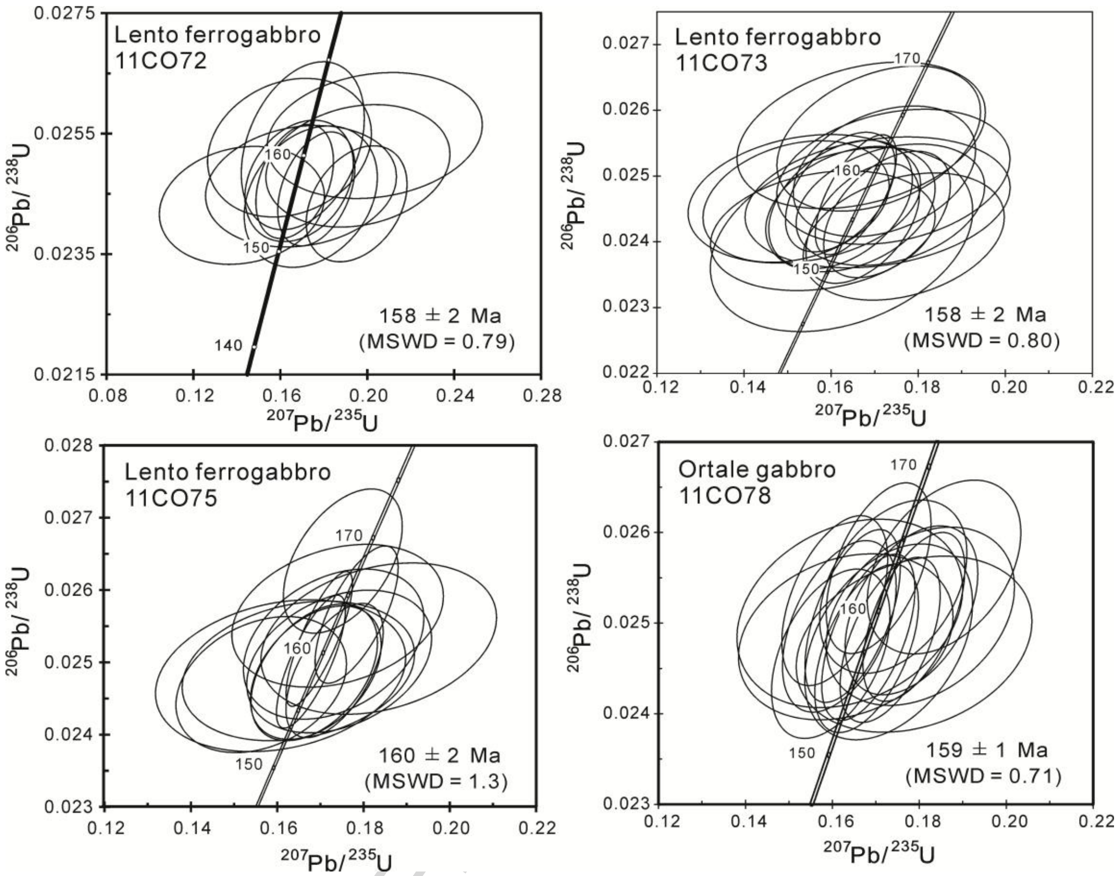

11CO72@2
11CO72@10
11CO75@4
11CO75@8
11CO73@5
11CO73@9
11CO78@2
11CO78@11
12BA10@3
12BA10@12
2BDL165@1
2BDL165@7
11CO73@1
baddeleyite
11CO73@5
baddeleyite
11CO73@8
baddeleyite
11CO73@12
baddeleyite

Figure 2



Lento ferrogabbro
11CO72
158 ± 2 Ma
(MSWD = 0.79)
Lento ferrogabbro
11CO73
158 ± 2 Ma
(MSWD = 0.80)
Lento ferrogabbro
11CO75
160 ± 2 Ma
(MSWD = 1.3)
Ortale gabbro
11CO78
159 ± 1 Ma
(MSWD = 0.71)
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

Figure 3

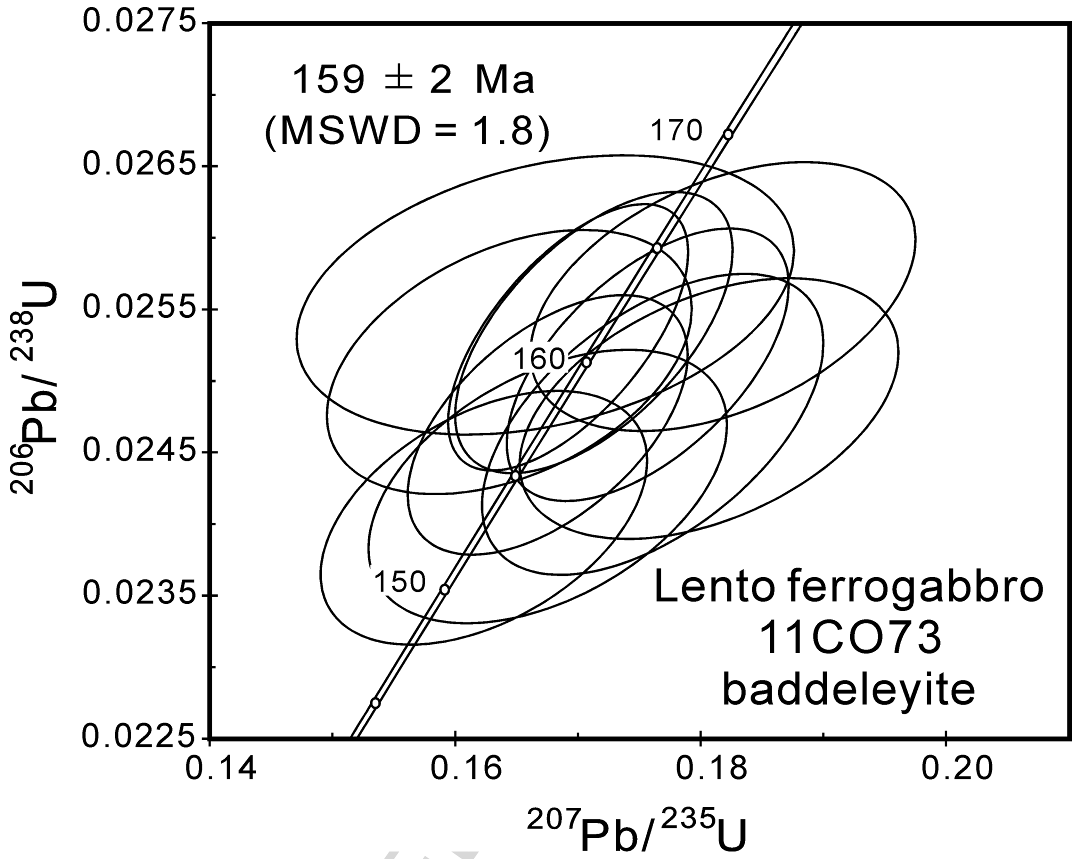
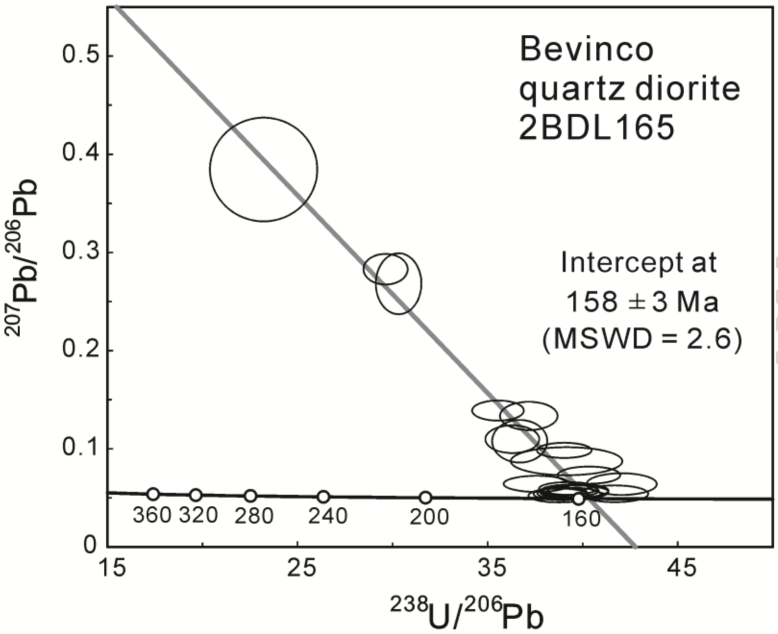
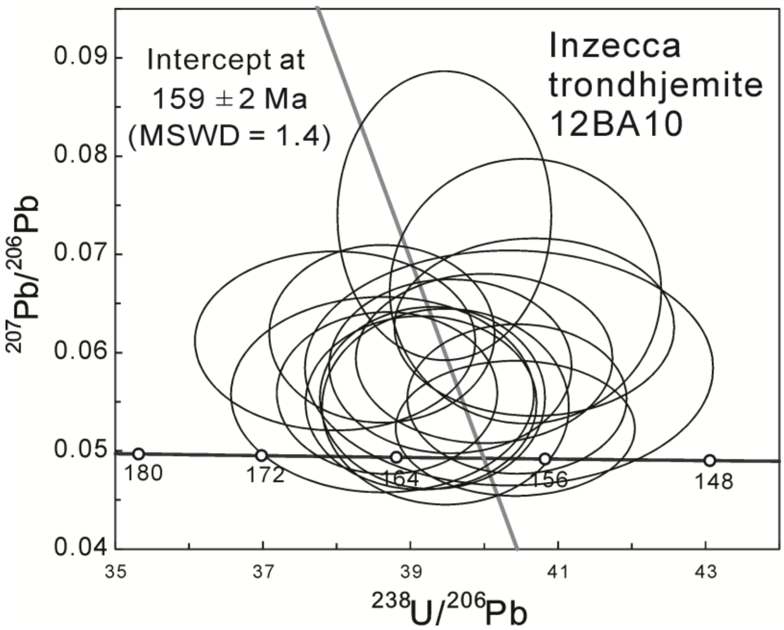

159 ± 2 Ma
(MSWD = 1.8)
170
160
150
Lento ferrogabbro
11CO73
baddeleyite
0.0275
0.0265
0.0255
0.0245
0.0235
0.0225
0.14
0.16
0.18
0.20
206Pb/238U
207Pb/235U

Figure 4

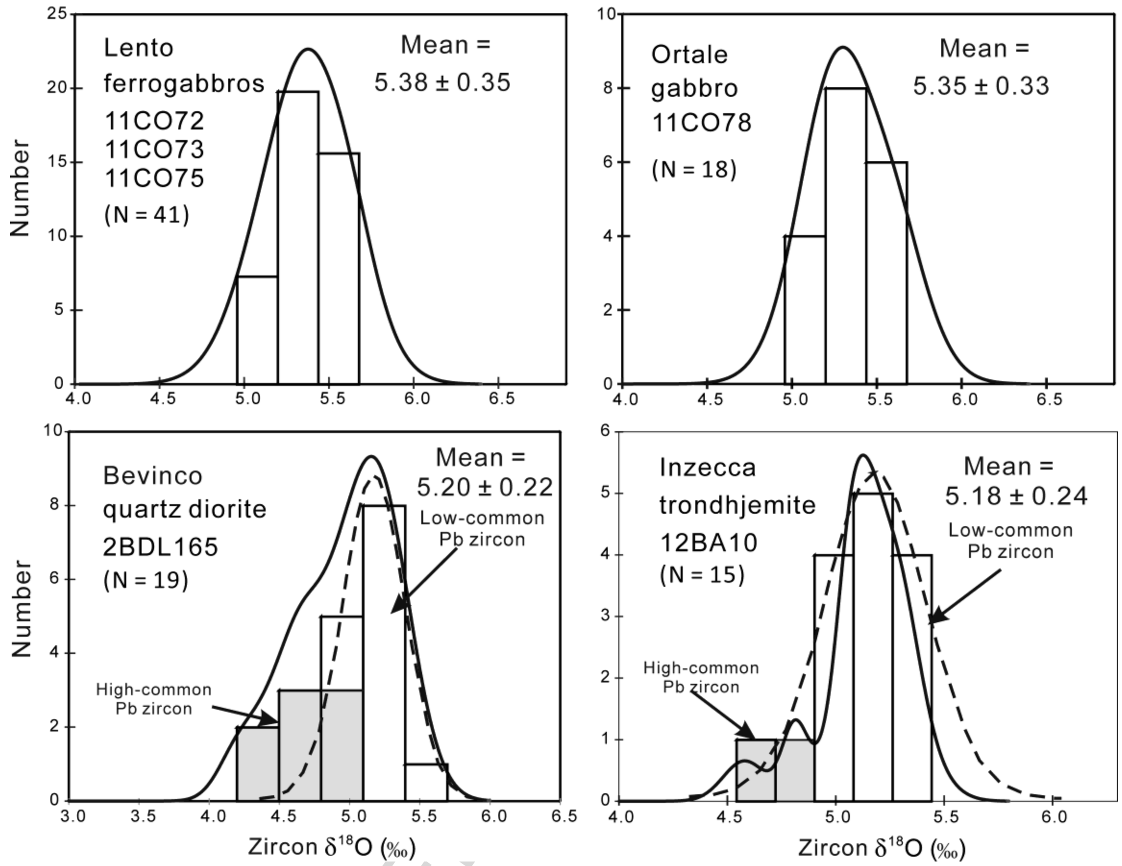


Bevinco
quartz diorite
2BDL165
Intercept at
158 ± 3 Ma
(MSWD = 2.6)
$^{207}Pb/^{206}Pb$
$^{238}U/^{206}Pb$
0.5
0.4
0.3
0.2
0.1
0
15
25
35
45
360 320 280 240 200 160



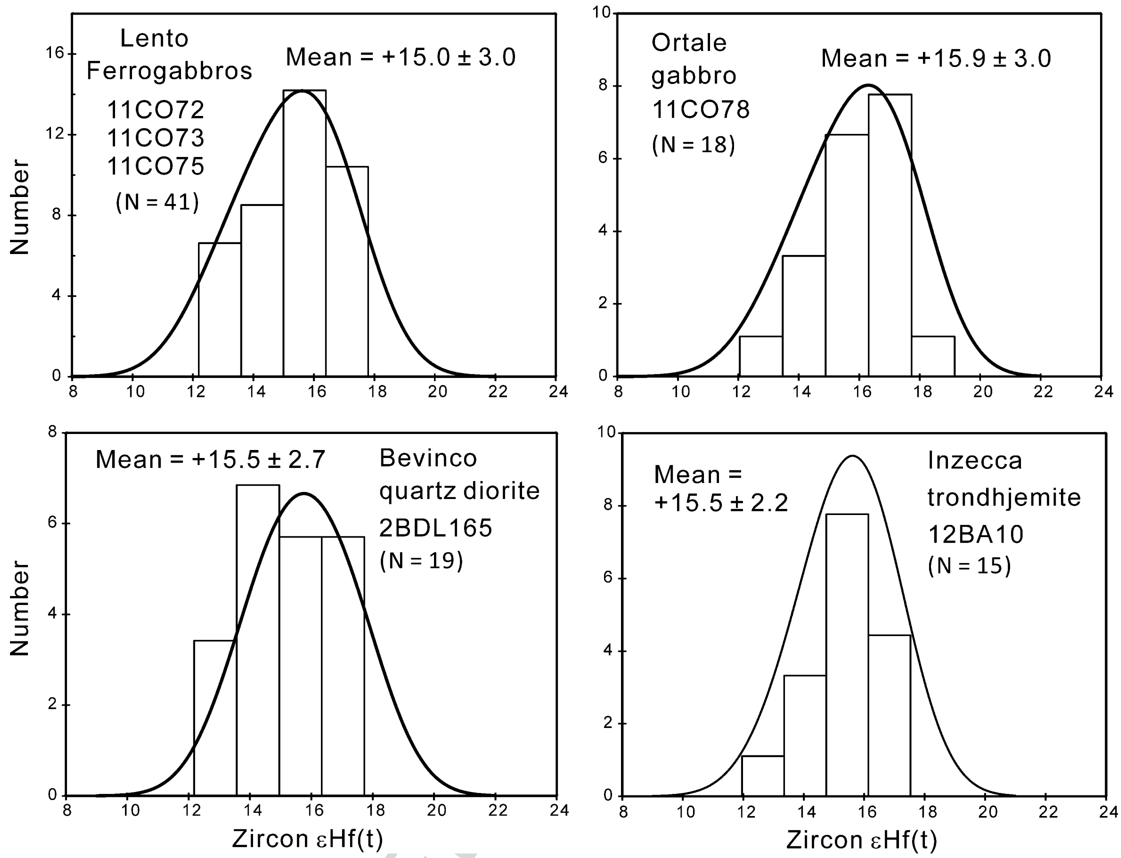
Intercept at
159 ± 2 Ma
(MSWD = 1.4)
Inzecca
trondhjemite
12BA10
$^{207}Pb/^{206}Pb$
$^{238}U/^{206}Pb$
0.09
0.08
0.07
0.06
0.05
0.04
35
37
39
41
43
180
172
164
156
148

Figure 5



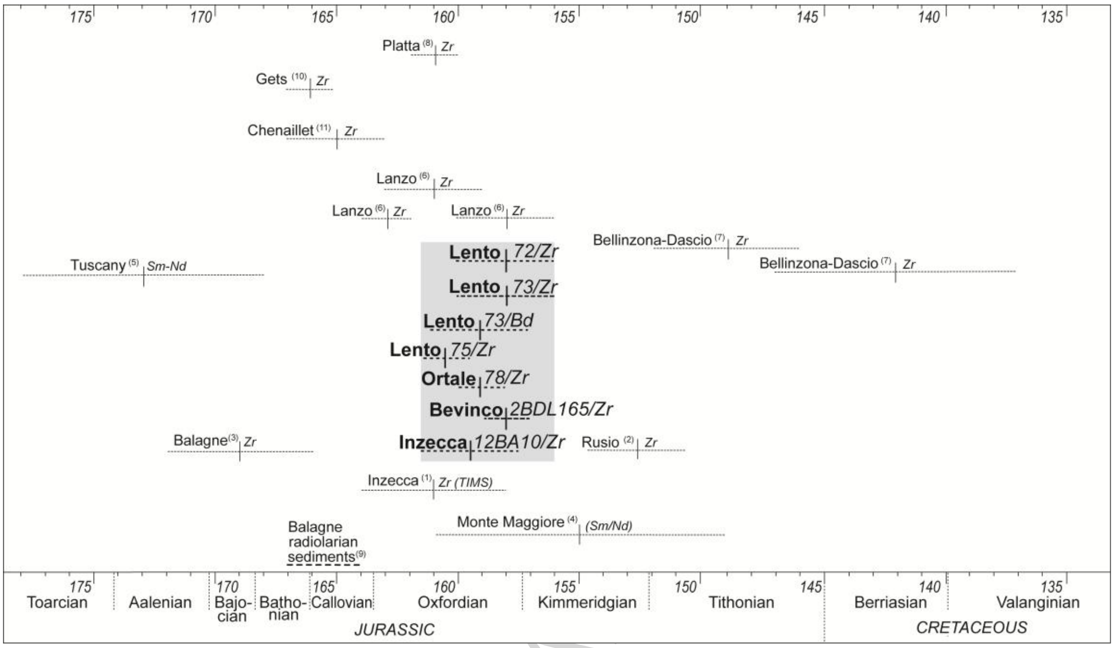
Lento
ferrogabbros
11CO72
11CO73
11CO75
(N = 41)
Mean =
5.38 ± 0.35
Number
Ortale
gabbro
11CO78
(N = 18)
Mean =
5.35 ± 0.33
Bevinco
quartz diorite
2BDL165
(N = 19)
Mean =
5.20 ± 0.22
Low-common
Pb zircon
High-common
Pb zircon
Inzecca
trondhjemite
12BA10
(N = 15)
Mean =
5.18 ± 0.24
Zircon δ18O (‰)

Figure 6



Lento
Ferrogabbros
11CO72
11CO73
11CO75
(N = 41)
Mean = +15.0 ± 3.0
Number
Ortale
gabbro
11CO78
(N = 18)
Mean = +15.9 ± 3.0
Mean = +15.5 ± 2.7
Bevinco
quartz diorite
2BDL165
(N = 19)
Number
Zircon εHf(t)
Mean =
+15.5 ± 2.2
Inzecca
trondhjemite
12BA10
(N = 15)
Zircon εHf(t)

Figure 7



175 170 165 160 155 150 145 140 135
Platta (8) Zr
Gets (10) Zr
Chenaillet (11) Zr
Lanzo (6) Zr
Lanzo (6) Zr
Lanzo (6) Zr
Bellinzona-Dascio (7) Zr
Bellinzona-Dascio (7) Zr
Tuscany (5) Sm-Nd
Lento 72/Zr
Lento 73/Zr
Lento 73/Bd
Lento 75/Zr
Ortale 78/Zr
Bevinco 2BDL165/Zr
Balagne(3) Zr
Inzecca 12BA10/Zr
Rusio (2) Zr
Inzecca (1) Zr (TIMS)
Monte Maggiore (4) (Sm/Nd)
Balagne radiolarian sediments(9)
Toarcian
Aalenian
Bajo-cian
Batho-nian
Callovian
Oxfordian
Kimmeridgian
Tithonian
Berriasian
Valanginian
JURASSIC
CRETACEOUS

Figure 8

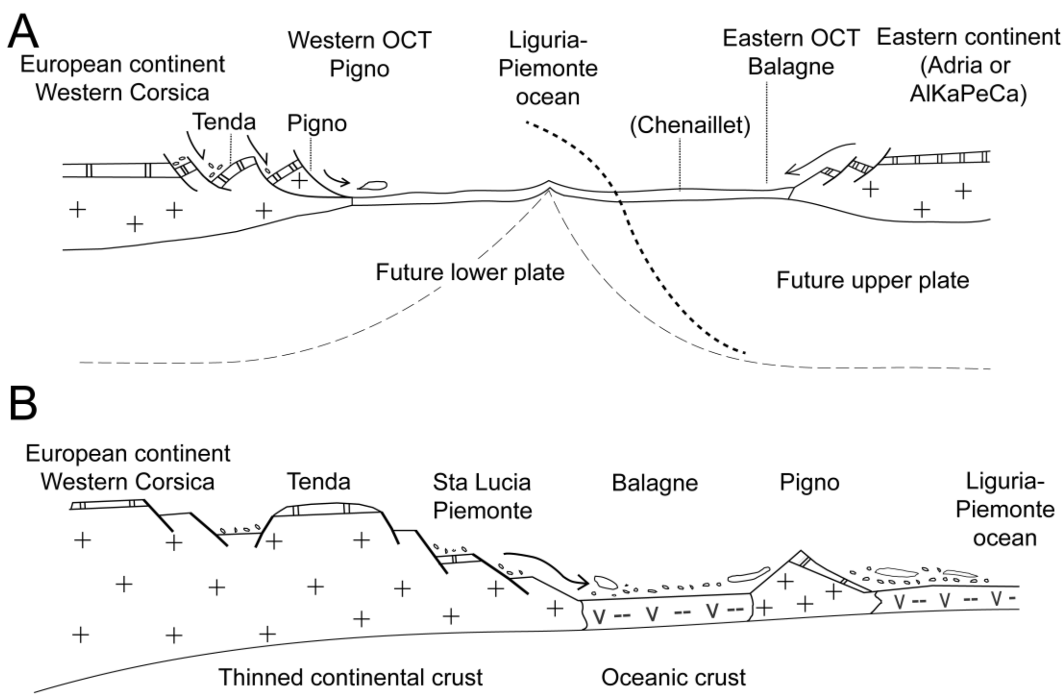

A
European continent
Western Corsica
Western OCT
Pigno
Liguria-
Piemonte
ocean
Eastern OCT
Balagne
Eastern continent
(Adria or
AlKaPeCa)
Tenda
Pigno
(Chenaillet)
Future lower plate
Future upper plate
B
European continent
Western Corsica
Tenda
Sta Lucia
Piemonte
Balagne
Pigno
Liguria-
Piemonte
ocean
Thinned continental crust
Oceanic crust

Figure 9

Highlights

► Ophiolitic gabbros and plagiogranites in Schistes Lustrés nappe formed at ~159 Ma.

► These ophiolitic rocks were cogenetic and derived from N-MORB type mantle.

► They represent the youngest remnants of the western Liguria-Piemonte ocean basin.